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AFFDL-TR-77-77

INCLUDING FLEET USAGE VARIABILITY IN RELIABILITY ANALYSES FOR BOTH SAFETY AND ECONOMIC LIMIT

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AUGUST 1977

20070924238

TECHNICAL REPORT AFFDL-TR-77-77
Final Report for Period September 1976 to March 1977

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AIR FORCE/56780/21 November 1977 — 500

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFFDL-TR-77-77	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Including Fleet Usage Variability in Reliability Analyses For Both Safety and Economic Limit	5. TYPE OF REPORT & PERIOD COVERED Final Report for Period Sep 1976 to Mar 1977 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert L. Neulieb	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Flight Dynamics Laboratory (AFFDL/FBE) Wright-Patterson Air Force Base, Ohio 45433	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 1367 Task 0336
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Flight Dynamics Laboratory (AFFDL/FBE) Wright-Patterson Air Force Base, Ohio 45433	12. REPORT DATE August 1977 13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Reliability
Aircraft
Structures

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Reliability tools have been developed which are capable of determining the probability of failing a given aircraft or the first aircraft in a fleet as a function of time, loading, and inspections. These methods, developed for the entire fleet, can easily be extended to include variations in usage across the fleet and to address the concept of economic life.

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FOREWORD

The research work reported herein was conducted within the Structural Integrity Branch, of the Structural Mechanics Division of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under project 1367, Structural Integrity for Military Aerospace Vehicles, and work unit 13670336, Life Analysis and Design Methods for Aerospace Structures. The research was conducted by R.L. Neulieb (AFFDL/FBE) from September 1976 to March 1977.

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SECTION I

INTRODUCTION

Probabilistic analyses for ensuring structural safety were introduced in the 1940's (Ref. 1). In terms of aircraft structures, much work has been directed to developing analyses suitable for determining the probability of the first failure in a fleet as a function of the number of flights or flight hours in a specified interval of operation (Ref. 2-7). These probability methods have evolved into powerful tools capable of addressing influences of material scatter, inspections, gust and maneuver loading parameters, full scale fatigue test item data, crack growth model parameters, and ground-air-ground cycles, among others.

One parameter which has not yet been incorporated is usage variations across the fleet. All aircraft in a fleet seldom experience identical severity of usage. There is a growing effort through the use of tracking programs to quantify these differences. A need exists to incorporate such variations into the reliability analyses.

In addition, the Air Force is not only interested in aircraft safety which is represented by the first catastrophic failure, but also in aircraft durability. Durability specifications are defined in terms of an aircraft's economic limit. The economic limit is reached when a fleet of aircraft can no longer be repaired with the expenditure of reasonable funds. This limit is reached with the occurrence of a number of failures which may not be catastrophic.

The probability of not only the first but also of subsequent failures of this type as a function of the number of flights or flight hours would be valuable in determining the economic limit.

If aircraft usage variations can be adequately represented by placing each member of the fleet in one of a small number of usage categories (perhaps twenty), existing reliability analysis procedures can be used to determine the probabilities of first and subsequent failures while accounting for the variations represented among the usage categories.

SECTION II

RELIABILITY CALCULATIONS FROM USAGE CATEGORIES

For a given fleet size, m, and statistically independent failures, the probability, P_0, of zero failures in a fleet can be determined. If for some time interval, T, the probability of failure for each aircraft in a fleet, p_i, has been determined, the probability of no failures in the fleet, P_0, would be given as follows:

$$P_0 = \prod_{i=1}^{m} (1 - p_i) \tag{1}$$

The probability, P_0, is the probability that the fleet would perform through time interval, T, without any of the failures considered in determining the p_i's. However, for a large fleet, both determining the m probabilities, p_i, and P_0, P_1, P_2, ... , P_n, the probability of no more than n failures through time interval, T, would be cumbersome.

If the individual aircraft were divided into k_0 categories, so that each aircraft in a category could be considered to have the same probability of failing in time interval, T, a significant simplification can be achieved. The categories would be selected so that the probability of any aircraft failing within a category would be nearly the same. Aircraft accumulate damage and are subjected to high loads at different rates. Both accumulated damage and severe loads affect the probability of failing. Mission mix, base location and flight hours can influence the probability of failing. Training, low altitude, high gross weight, air-to-air combat, air-to-ground combat, and ferry missions among others each tend to damage aircraft at different rates. When gust sensitive aircraft perform low altitude missions over mountains as opposed to plains, deserts, or water, they are subjected to more severe turbulence and hence accumulate damage faster and have an increased probability of failing. Aircraft generally are rotated so that each aircraft throughout its life performs several missions and operates from different bases. For some time interval, the aircraft with similar mission mixes, severity of base locations, and flight hours would be placed in the same category.

Probabilities of failures in the fleet as a function of time are frequently desired. The probability of failing a member of each category would then be calculated for several times of interest. The assignment of aircraft to different categories and even the number of categories could be a function of time due to rotation.

The probability for the failure of a single aircraft in each of the categories and time intervals would be established. Methods such as those developed in Ref. 7 could be used within each category instead of for the entire fleet. This division of aircraft into different usage categories would necessitate the determination of only a small number (perhaps twenty) of probabilities of failing and permit the use of well known properties of certain distributions to calculate probabilities of first and subsequent failures in the fleet.

The probability of $s = 0, 1, 2, \ldots, j$ independent failures within a category is given by the binomial probability law. Under certain conditions, the binomial probability law can be approximated by the Poisson probability law (Ref. 8). Generally for a large number of members and a small probability of failing this approximation is valid. In Ref. 9, there are graphs comparing the two laws for five members with a probability of 0.3 and ten members with a probability of 0.15. Various guidelines for the approximation are given in Refs. 8 through 11. Since probabilities for the entire fleet are desired, and only a few failures can be tolerated, this approximation should be reasonable. Some comparisons between the two laws are also given in Section III.

The Poisson probability law (Ref. 8) can be expressed as

$$P_{ks} = e^{-n_k p_k} \frac{(n_k p_k)^s}{s!} \tag{2}$$

where subscript k identifies the category; s is the number of failures in the category; n_k is the number of aircraft in the k^{th} category; p_k is the probability of failing for each aircraft in the k^{th} category, and P_{ks} is the probability of exactly s failures in the k^{th} category. It should be noted that the two parameters n_k and p_k always appear as a product. Hence the Poisson probability law can be expressed as a one parameter distribution. By letting $\lambda_k = n_k p_k$, we obtain

$$P_{ks} = e^{-\lambda_k} \frac{\lambda^s}{s!} \tag{3}$$

By using a summation property of Poisson distributed population, the probabilities of no more than n failures in a fleet can be readily calculated. As indicated in Ref. 8, the number of failures in a population composed of k_0 categories each with failures that are Poisson distributed is Poisson distributed where the λ parameter is the sum of the λ_k's for each category. Hence if P_{fs} is the probability of exactly s failures in the fleet, we have

$$P_{fs} = e^{-\lambda} \frac{\lambda^s}{s!} \tag{4}$$

where

$$\lambda = \sum_{k=1}^{k_0} \lambda_k \tag{5}$$

or

$$\lambda = \sum_{k=1}^{k_0} n_k p_k \tag{6}$$

The probability of no more than n failures in a fleet is given by the sum of the probabilities of all possible numbers of failures less than or equal to n. The probability of zero failures must be included. Hence, P_n, the probability of no more than n failures in the fleet is given by

$$P_n = \sum_{s=0}^{n} P_{fs} \tag{7}$$

The parameter λ for the fleet can be interpreted in terms of the size of the fleet and an average probability of failing any member of the fleet. Defining λ as the product of the number of aircraft in the fleet, n_f, and an average probability of any aircraft in the fleet failing, p_f, we have

$$\lambda = n_f p_f \tag{8}$$

one can show that p_f is simply the arithmetic mean of the probabilities of failing each member of the fleet. Using Eqs. 6 and 8, we find

$$n_f p_f = \sum_{k=1}^{k_0} n_k p_k \tag{9}$$

or

$$p_f = \frac{1}{n_f} \sum_{k=1}^{k_0} n_k p_k \tag{10}$$

The right hand side of Eq. 10 is the arithmetic mean of the probabilities of failing the individual members of the fleet.

The division of aircraft into a small number of usage categories and the use of the Poisson approximation to the binomial probability law permits extremely efficient calculations of the probabilities of no more than n failures in a fleet. Four steps are necessary for the calculation of the probabilities of failure in the fleet. First, p_k, the probability of failure of an aircraft in each usage category is determined. Methods such as those developed in Ref. 7 can be used. Second, λ for the fleet is determined by using Eq. 6. Third, by using this λ in the Poisson probability law (Eq. 4), the probability of exactly s failures ($s = 0, 1, \ldots, n$) in the fleet are calculated. And finally, these probabilities are summed according to Eq. 7 in order to obtain the probabilities of no more than n failures. Only the first step places any restriction on the number of categories which it is practical to use. The three other steps can be easily accomplished on a desk top or programmable calculator for any number of categories. If the probability of failing an individual member is known for each category, the influences of varying the number of aircraft in each category are easily determined.

SECTION III

EXAMPLE

Consider a hypothetical fleet which for its design lifetime can be divided into six categories. Category 1 is composed of a small number of severely used demonstration aircraft. Category 2 is composed of aircraft frequently used for low altitude missions, while the other four categories are composed of less severely used aircraft. The probability of failing an aircraft in a particular category is the probability that an aircraft in that category will fail catastrophically during its design lifetime. For other problems, different time intervals, such as the time intervals between inspections, can be used.

The output given in Table I was generated on a Hewlett-Packard HP9830 programmable calculator by using the Poisson approximation as described in Section II. The code and necessary inputs are described in the Appendix. This code not only gives the probability of no more than n failures in a fleet but also the probabilities of exactly s failures (s = 0, 1, ... , n) in each category and the average probability of failing an aircraft in the fleet.

TABLE I

EXAMPLE

```
CATEGORY 1     PROB.  OF FAILING= 0.01     NO.  OF STRUCTURES= 17

PROB.  OF FAILING EXACTLY 0     STRUCTURES= 0.843664817
PROB.  OF FAILING EXACTLY 1     STRUCTURES= 0.143423019
PROB.  OF FAILING EXACTLY 2     STRUCTURES= 0.012190957
PROB.  OF FAILING EXACTLY 3     STRUCTURES= 6.90821E-04


CATEGORY 2     PROB.  OF FAILING= 2.00000E-03   NO.  OF STRUCTURES= 56

PROB.  OF FAILING EXACTLY 0     STRUCTURES= 0.894044258
PROB.  OF FAILING EXACTLY 1     STRUCTURES= 0.100132957
PROB.  OF FAILING EXACTLY 2     STRUCTURES= 5.60745E-03
PROB.  OF FAILING EXACTLY 3     STRUCTURES= 2.09345E-04


CATEGORY 3     PROB.  OF FAILING= 7.00000E-04   NO.  OF STRUCTURES= 127

PROB.  OF FAILING EXACTLY 0     STRUCTURES= 0.914937063
PROB.  OF FAILING EXACTLY 1     STRUCTURES= 0.081337905
PROB.  OF FAILING EXACTLY 2     STRUCTURES= 3.61547E-03
PROB.  OF FAILING EXACTLY 3     STRUCTURES= 1.07138E-04


CATEGORY 4     PROB.  OF FAILING= 2.00000E-04   NO.  OF STRUCTURES= 323

PROB.  OF FAILING EXACTLY 0     STRUCTURES= 0.937442365
PROB.  OF FAILING EXACTLY 1     STRUCTURES= 0.060558777
PROB.  OF FAILING EXACTLY 2     STRUCTURES= 1.95605E-03
PROB.  OF FAILING EXACTLY 3     STRUCTURES= 4.21202E-05


CATEGORY 5     PROB.  OF FAILING= 1.00000E-04   NO.  OF STRUCTURES= 257

PROB.  OF FAILING EXACTLY 0     STRUCTURES= 0.974627434
PROB.  OF FAILING EXACTLY 1     STRUCTURES= 0.025047925
PROB.  OF FAILING EXACTLY 2     STRUCTURES= 3.21866E-04
PROB.  OF FAILING EXACTLY 3     STRUCTURES= 2.75732E-06


CATEGORY 6     PROB.  OF FAILING= 5.00000E-05   NO.  OF STRUCTURES= 423

PROB.  OF FAILING EXACTLY 0     STRUCTURES= 0.979072093
PROB.  OF FAILING EXACTLY 1     STRUCTURES= 0.020707375
PROB.  OF FAILING EXACTLY 2     STRUCTURES= 2.18980E-04
PROB.  OF FAILING EXACTLY 3     STRUCTURES= 1.54381E-06


FOR THE FLEET OF 1203     STRUCTURES, AV.  PROB. = 4.00956E-04

PROB.  OF FAILING NO MORE THAN 0     STRUCTURES= 0.617330958
PROB.  OF FAILING NO MORE THAN 1     STRUCTURES= 0.915100546
PROB.  OF FAILING NO MORE THAN 2     STRUCTURES= 0.986915126
PROB.  OF FAILING NO MORE THAN 3     STRUCTURES= 0.998461714
PROB.  OF FAILING NO MORE THAN 4     STRUCTURES= 0.999854088
PROB.  OF FAILING NO MORE THAN 5     STRUCTURES= 0.999988410
```

From Table I, the probability that no aircraft will fail catastrophically during one design lifetime of the fleet is 0.6173. This is the probability that the fleet will perform for one design lifetime without any catastrophic failures. Likewise, the probability that the fleet will perform for one design lifetime with at most one catastrophic failure is 0.9151.

The calculations required for this example could be performed for various times during the fleet lifetime, and the probabilities of no more than s failures could be plotted as functions of time.

The validity of the calculations of the probability of exactly s failures in each category depends on the number of members and the probability of failing as discussed in Section II. As guidelines, the probabilities of failing exactly and no more than s members of each category have been calculated using the binomial probability law. By using the average probability of failing obtained from the Poisson approximation and summation property, the probabilities of exactly and no more than s failures in the fleet are calculated from the binomial probability law and are given in Table II. These probabilities for the fleet are not exact for the given combination of categories since the binomial probability law does not possess a convenient summation property when both the number of members and probability of failing differ among the categories. It will be observed that the probabilities, given in Tables I and II, of no more than s failures (s = 0, 1, ... , s) in the fleet agree to at least 4 decimal places.

TABLE II

PROBABILITIES OF EXACTLY AND NO MORE THAN s FAILURES USING THE BINOMIAL PROBABILITY LAW

PROB. OF FAILING= 0.01 NO. OF STRUCTURES= 17

NO.	EXACTLY	NO MORE THAN
0	0.842943	0.842943
1	0.144748	0.987691
2	0.011697	0.999388
3	0.000591	0.999979

PROB. OF FAILING= 2.00000E-03 NO. OF STRUCTURES= 56

NO.	EXACTLY	NO MORE THAN
0	0.893944	0.893944
1	0.100322	0.994266
2	0.005529	0.999795
3	0.000199	0.999995

PROB. OF FAILING= 7.00000E-04 NO. OF STRUCTURES= 127

NO.	EXACTLY	NO MORE THAN
0	0.914909	0.914909
1	0.081392	0.996301
2	0.003592	0.999893
3	0.000105	0.999998

PROB. OF FAILING= 2.00000E-04 NO. OF STRUCTURES= 323

NO.	EXACTLY	NO MORE THAN
0	0.937436	0.937436
1	0.060570	0.998007
2	0.001951	0.999958
3	0.000042	0.999999

PROB. OF FAILING= 1.00000E-04 NO. OF STRUCTURES= 257

NO.	EXACTLY	NO MORE THAN
0	0.974626	0.974626
1	0.025050	0.999677
2	0.000321	0.999997
3	0.000003	1.000000

PROB. OF FAILING= 5.00000E-05 NO. OF STRUCTURES= 423

NO.	EXACTLY	NO MORE THAN
0	0.979072	0.979072
1	0.020708	0.999780
2	0.000218	0.999998
3	0.000002	1.000000

PROB. OF FAILING= 4.00956E-04 NO. OF STRUCTURES= 1203

NO.	EXACTLY	NO MORE THAN
0	0.617271	0.617271
1	0.297860	0.915131
2	0.071806	0.986937
3	0.011531	0.998468
4	0.001388	0.999855
5	0.000133	0.999989

SECTION IV

CONCLUSIONS

For a reasonable number of usage categories, the methods developed in Ref. 7 can be readily extended to the calculation of the reliability of a fleet by including both usage variations across the fleet and failures subsequent to the first.

Both the questions of safety and economic limit can be addressed by using existing reliability tools since the probability of first and subsequent failures can be determined for given usages of the fleet.

The effects of alternate fleet usages on the probabilities of failures in the fleet can be investigated by using existing reliability tools.

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APPENDIX

CALCULATOR CODE

The code given below is programmed in BASIC compatible with the Hewlett-Packard H-P9830 programmable calculator. Output from this program is given in Section III. Three different inputs from the keyboard are required and each input is indicated on the display.

Inputs

(1) One number, the number of categories.
(2) Two numbers, first, the number of failures to be printed for each category and second, the number of failures to be printed for the fleet.
(3) Required for each category, two numbers, first, the probability of failing a structure in the given category and second, the number of structures in the category.

For the example in Section III, the number of categories is 6. The numbers of failures printed are 3 for each category and 5 for the fleet. The probability of failing and the number of structures in each category are given in the output.

The dimension statement, line 10, controls the number of categories possible. The variables, P and N, must be dimensioned at least the number of categories to be used. In the code listed, this number is 25. The maximum number of failures for which probabilities can be calculated is controlled in this program by the largest number the calculator can use. This number is approximately 1×10^{100}.

As indicated in Eq. (2), factorials of the number of failures are used in the calculation of probabilities. Seventy factorial exceeds $1x10^{100}$; hence, this program is limited to 69 failures. The variable F, the factorials, in the Dimension statement, line 10, must be dimensioned at least one greater than the maximum number of failures to be calculated as zero factorial is also stored in F. This code is written so that 69 failures can be considered.

CALCULATOR CODE

```
10 DIM F[70],P[25],N[25]
20 F[1]=F[2]=1
30 DISP "NO. OF CATEGORIES";
40 INPUT N
50 DISP "NO. OF FAILURES TO BE PRINTED CATEGORY AND FLEET";
60 INPUT N1,N2
70 IF N1>N2 THEN 100
80 N3=N2
90 GOTO 110
100 N3=N1
110 IF N3 <= 1 THEN 150
120 FOR I=1 TO N3-1
130 F[I+2]=(I+1)*F[I+1]
140 NEXT I
150 P7=P9=N9=0
160 FOR I=1 TO N
170 DISP "PROB. OF FAILING AND NO. OF STRUCTURES IN CATEGORY";I;
180 INPUT P[I],N[I]
190 N9=N9+N[I]
200 P9=P9+N[I]*P[I]
210 NEXT I
220 FOR I=1 TO N
230 PRINT "CATEGORY";I;"PROB. OF FAILING=";P[I];"NO. OF STRUCTURES=";N[I]
240 PRINT
250 FOR J=1 TO N1+1
260 P1=EXP(-N[I]*P[I])*(N[I]*P[I])^(J-1)/F[J]
270 PRINT "PROB. OF FAILING EXACTLY";J-1;"STRUCTURES=";P1
280 NEXT J
290 PRINT
300 PRINT
310 NEXT I
320 PRINT "FOR THE FLEET OF";N9;"STRUCTURES, AVE. PROB.=";P9/N9
330 PRINT
340 FOR I=1 TO N2+1
350 P8=EXP(-P9)*P9^(I-1)/F[I]
360 P7=P7+P8
370 PRINT "PROB. OF FAILING NO MORE THAN";I-1;"STRUCTURES=";P7
380 NEXT I
390 PRINT
400 PRINT
410 PRINT
420 GOTO 30
430 END
```